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LIFT MEASUREMENTS ON SMALL-SCALE

FLAT PLANING SURFACES

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Introduction

Because of the need for design information for seaplanes and planing boats, the hydrodynamics of planing has been the object of much experimental and some theoretical study in the last twenty-five years. More recently the subject has become of interest in the field of hydroballistics. For practical purposes the chief source of information has been the extensive tests made with small models in towing tanks, both on specific hulls and on simple geometric forms. These latter tests are useful for understanding the basic phenomena of planing, and experiments on flat plates have been particularly helpful in this respect.

An immediate question for the experimenter is the nature and magnitude of the so-called scale effect, if any, which may appreciably influence the test results. The term "scale effect" as used in planing work includes both viscous and surface tension effects, but not gravity effects, which are modeled by maintaining the proper Froude number. The problem was first considered by Sottorf,[1,2*] who carried out a systematic series of tests on flat plates of different scale at a constant Froude number. Sottorf concluded that the hydrodynamic pressure distribution on the plate was not noticeably affected by scale, while the shear forces , on the other hand, were very sensitive to the size of model, both because of the usual viscous effects and also because of the alteration of the flow near the edges by surface tension. Thus, although the force parallel to the plate, which largely determines the drag at small attack angles, cannot be modeled properly, the force normal to the plate (or for small angles, the lift force) is unaffected by scale so long as the proper Froude number is maintained.

In spite of Sottorf's conclusions on this point, however, there have recently been expressions of doubt as to the validity of lift force measurements made with small models. For example, some tests made by Falkemo and Adlercreutz have been reported[3] in which the measurements on a model 5 inches wide were of the order of 20% higher than that value predicted from an empirical formula based on Sottorf's data. The

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* See references at end of report.

discrepancy was ascribed to scale effect though Sottorf[2] had successfully
used a model of 3-in. width for a similar measurement. In view of the
importance of small models in planing work, a program of systematic
tests on scale effect has been initiated in the Free Surface Water Tunnel
of the Hydrodynamics Laboratory.[4] The results of tests on flat plates to
date are reported herein.

Modeling and Scale Effect

Since the theory of modeling can readily be found in previous reports
and elsewhere,[2,5] it will not be discussed here, and only a brief outline of
experimental procedures will be included. In order to study the scale ef-
fect on flat plates, Sottorf proceeded as follows: A run was made with a
given width flat plate carrying a fixed load at a fixed velocity, and the
corresponding attack angle and wetted length noted. Then another, say
larger, plate was run at a higher velocity such that the Froude number
$F = V/\sqrt{gb}$, where V is the velocity, g the acceleration of gravity, and
b the plate width, was the same as before. Also, the load was increased
the appropriate amount so as to obtain the same load coefficient
$C_{L_b} = L/\frac{1}{2}\rho V^2 b^2$, where L is the load on the plate and ρ is the density
of the water. At the same attack angle as used previously, the wetted
length l was noted. Now, according to the theory of similitude, the
length-width ratio l/b in both cases will be the same in general only if
gravity is the single factor influencing the flow pattern, that is, only if
there is no scale effect.

This procedure was carried out by Sottorf for a large range of plate
widths for the constant Froude number of 3.47. His results are shown in
Fig. 1, which is reproduced from Ref. 2. Sottorf did not repeat the attack
angle exactly since it was experimentally more convenient to take a whole
set of runs at various attack angles and then fair a curve through the data,
as shown in Fig. 1. The important result is that there is no systematic
deviation of the experimental points from the averaging curve. This data
(Fig. 1) enabled Sottorf to conclude that there was no scale effect on the
lift of flat plates, at least in the range he covered, which, it will be noted,
extends to models as small as 3 in. in width.

Another procedure for measuring the scale effect on the left is as
follows: The model is mounted at a fixed attack angle and length-width

ratio and the lift force measured at the given velocity. Then a different
width model is mounted at the same attack angle and length-width ratio,
the velocity being changed so that the Froude number is the same as in the
first run, and the corresponding lift force then measured. Again the simili-
tude theory states that the lift coefficients $C_{L_s} = L / \frac{1}{2}\rho V^2 \mathcal{L}b$, based on the
wetted area, will in general be equal only if there is no scale effect. Al-
though this approach is more suitable for the experiments in the Free Sur-
face Tunnel, it was thought better to begin with a series of tests conforming
to Sottorf's plan, so that direct comparison of data would be possible, rather
than resorting to faired curves or empirical equations such as Falkemo and
Adlercreutz employed. Later parts of the report include data taken in ac-
cordance with the second scheme just outlined.

Test Equipment

The Free Surface Tunnel is a water tunnel of the closed circuit type
with the flow in the working section bounded on three sides by lucite windows,
the upper surface being left free. The flow moves through the working sec-
tion at from 12 to 27 fps, the measured velocity profile being sufficiently
rectangular to insure accurate results in the working region near the free
surface. The lower limit on velocity is imposed in order to avoid the
longitudinal surface curvature that develops at or below the velocity of a
gravity wave in the channel. The working section, which measures 20 in.
wide by 20 in. deep by 8 ft long, is designed for use with models of about
2 in. width, but somewhat larger sizes can sometimes be used without ex-
cessive blockage. The tunnel is described in more detail in Refs. 4 and 7.

For the present tests a one-component mechanical balance was de-
signed and constructed to measure the lift force. The balance is of the
parallelogram type with grease-sealed ball bearings at the four pivots. A
simple dashpot damps any oscillations, and a counterweight is provided so
that the lift force is measured directly by placing weights on the pan. Tests
indicate the balance can measure to about ± 0.002 lb. An advantage of the
parallelogram arrangement is that the angle of attack of the model remains
unchanged even if the model moves vertically. This one-component balance
was used for the earlier tests, and the tunnel three-component balance[9] was
used for the remainder. The latter is capable of measuring forces to
± 0.001 lb.

The models used are lucite plates of several widths all 3/8-in. thick. The transparency of the model enables the experimenter to observe the wetted surface directly, as was done in the experiments of Sottorf. The attack angle is set by means of a leveling protractor with a precision of about ± 0.1 degree. Velocity measurements are made using the standard tunnel velocity manometer. While the velocity is subject to some fluctuations, it is believed that most of the velocity readings are accurate to about $\pm 1\%$.

A view of a typical planing model mounted in the tunnel is shown in Fig. 2. The most difficult part of the measurements is the determination of the wetted length. In order to conform with Sottorf's convention, the wetted length is measured at the quarter width of the plate. Because the forward spray sheet falls back into the oncoming flow, the wetted length fluctuates about a mean value, which is obtained by visual observation. Some idea of the fluctuation can be obtained from Fig. 3 where the two photographs shown were taken a few seconds apart. Note the forward spray clinging to the under side of the plate. At small attack angles, say less than 4°, the error introduced by the fluctuation may be appreciable if the wetted length is rather short. For the most part, however, it was found possible to repeat readings within a few percent, and it seems that the over-all precision of most of the experiments was better than $\pm 4\%$, which is adequate for the work at hand. The precision is improved if one avoids very small attack angles and small wetted lengths.

Results of Experiments

The results of some preliminary tests presented in Figs. 4 and 5 are a continuation of the experiments of Sottorf, as shown in Fig. 1, with which they can be compared for scatter. The data of Sambraus,[6] who extended Sottorf's work to high Froude numbers, is also shown. The agreement of the Free Surface Tunnel data with the experiments of Sottorf (Figs. 4 and 5) is excellent, about as good as the self-consistency of Sottorf's results in Fig. 1. The curve for $C_{L_b} = 0.0545$ in Fig. 5 is particularly significant since it shows that the agreement between the Free Surface Tunnel tests using small models (circles) and Sottorf's data (squares), is as good as Sambraus' check runs (triangles) in which he used the same

size model as Sottorf. Hence the data again confirm Sottorf's conclusion that there is no scale effect on the lift.

Some further tests at higher Froude numbers were run in order to compare with the results of Sambraus in this range, but here the Free Surface Tunnel data usually showed a consistently lower lift force. The source of the discrepancy was found to be that the lateral edges, or chines, of the model plates were not sufficiently sharp. A slight rounding of these corners affects the lift very noticeably, as can be seen from Fig. 6. The recent theoretical work of Armstrong[10] on the separation point of a free streamline from a solid body indicates that such a critical effect might be expected.

With the edge difficulty corrected, a series of experiments were made to compare directly with the latest data at high Froude number from the Langley Field Tank of the NACA.[11] These latter tests were run on a plate of 4-in. width and were known to agree well with those of Sambraus which were run with a 5.9-in. width plate. The Free Surface Tunnel results are presented in Fig. 7 along with the NACA results, for comparison. As can be seen, the agreement is excellent. It can be concluded then, in agreement with the original findings of Sottorf, that if proper care is taken, accurate lift measurements can be made on models as small as 2 inches in width.

Remarks on Empirical Formulas and on Planing Theory

It has been pointed out by Weinstein and Kapryan[11] that the existing empirical formulas, based on tests at low Froude number, are inaccurate at higher Froude number. It was also shown in Ref. 12 that these formulas would not be adequate for very low or very high aspect ratio. Hence, due caution should be exercised to see that such formulas are not extrapolated into any range beyond that for which they represent the test data.

A review of the planing theory for flat plates of zero and infinite aspect ratio was also given in Ref. 12, and an attempt was made to construct a physically reasonable interpolation formula for intermediate aspect ratios. This approach did not include the effect of gravity; that is, it corresponded to very high Froude number, and the computed lift was compared with the available empirical formulas extrapolated to high Froude number. While the agreement with the empirical formula was very good, it now appears,

in view of the recent NACA and Free Surface Tunnel tests, that the agree-
ment with actual experiments at high Froude number is poor. No explana-
tion for this result is evident, but it would seem that experiments to check
the zero and infinite aspect ratio theory directly would be of considerable
value.

Conclusions

The following conclusions are offered on planing flat plates:

1. A very slight rounding of the chines on a small model results in
an appreciable reduction in the measured lift.

2. With a carefully made model, lift measurements without scale
effect can be made on a plate as small as 2 inches wide.

3. Present empirical formulas and the interpolation method of Ref.
12 do not agree with recent experiments at high Froude number.

Acknowledgments

Symbols

b,   plate width, or beam

C_{L_b},   lift coefficient based on beam, $C_{L_b} = L / \frac{1}{2} \rho V^2 b^2$

C_{L_s},   lift coefficient based on wetted area, $C_{L_s} = L / \frac{1}{2} \rho V^2 \ell b$

F,   Froude number, $F = V / \sqrt{g b}$

g,   acceleration due to gravity

L,   lift force

ℓ,   wetted length measured at quarter-width

V,   flow velocity

a,   attack angle, or trim

ρ,   fluid density

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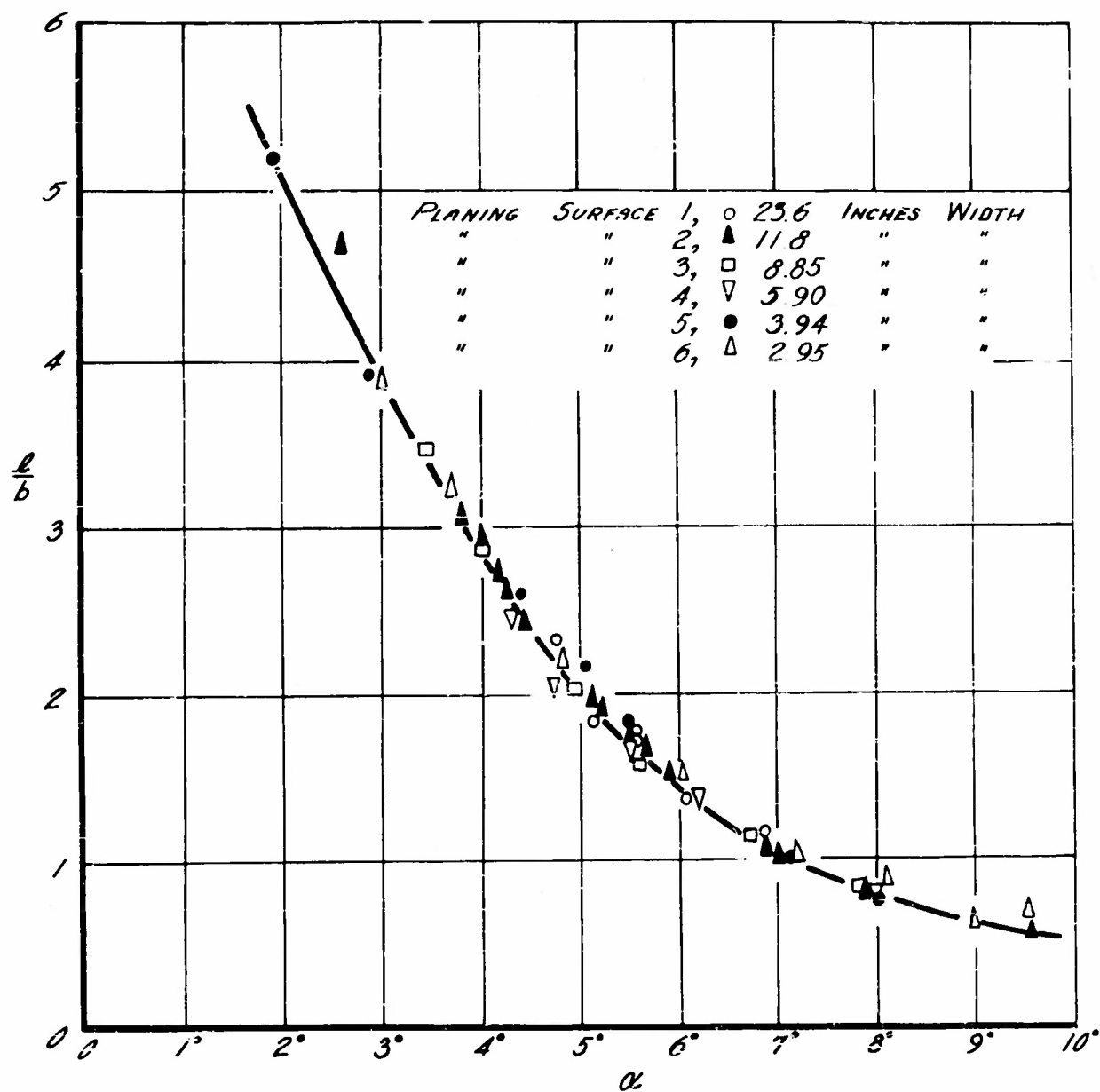
Fig. 1 - Measurements of Sottorf showing absence of scale effect on the length-width ratio, and hence lift, of a flat planing surface.
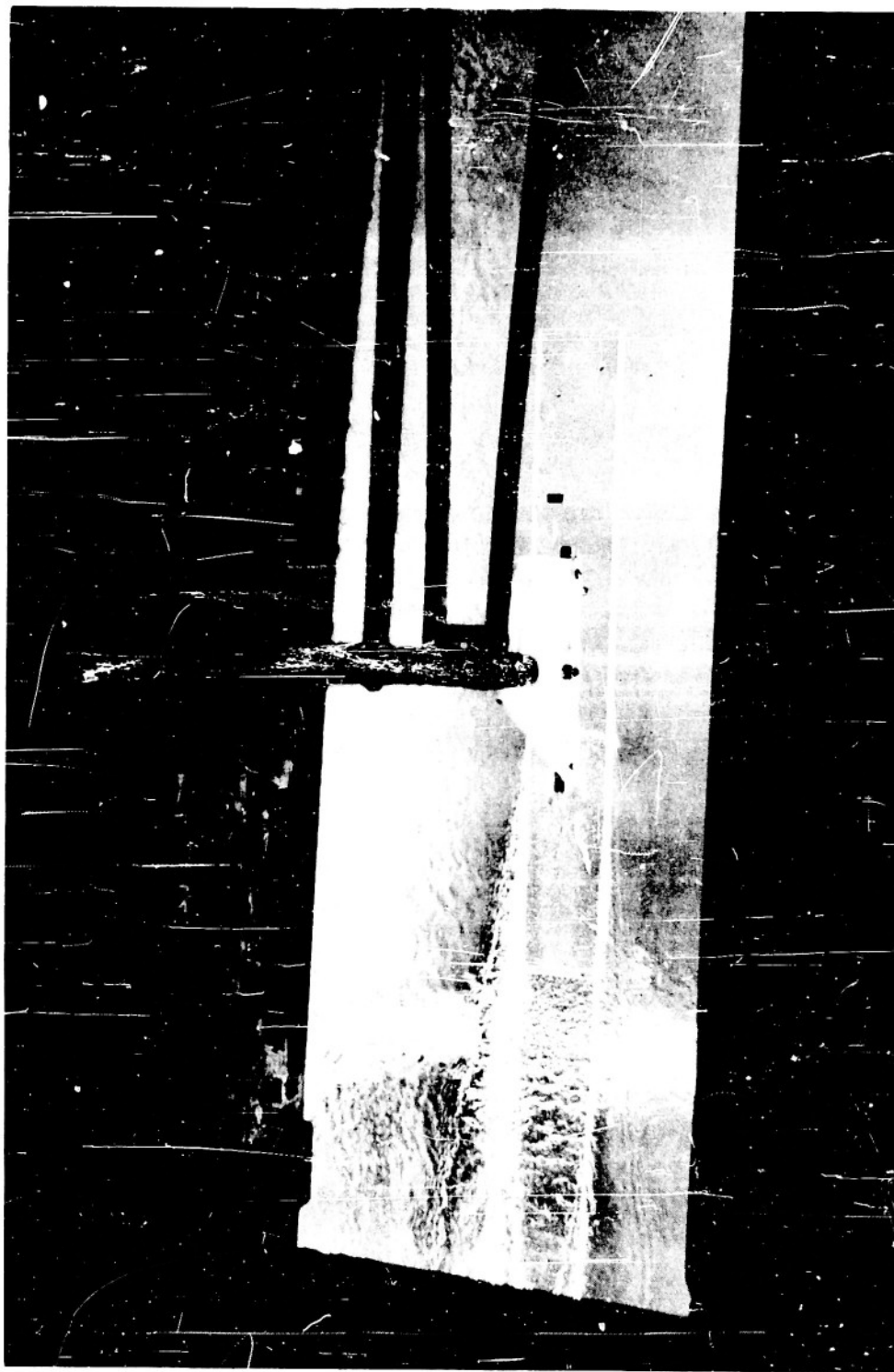
Fig. 2 - A flat plate lucite model planing in the Free Surface Tunnel. (Width, 2 in.; wetted length, 6 in.; attack angle, 4°; flow velocity, 12 fps).
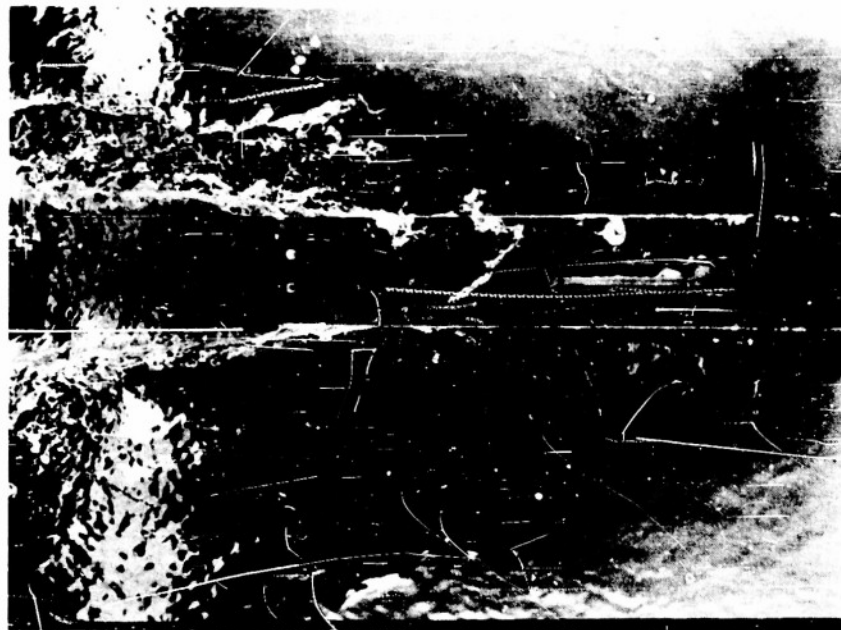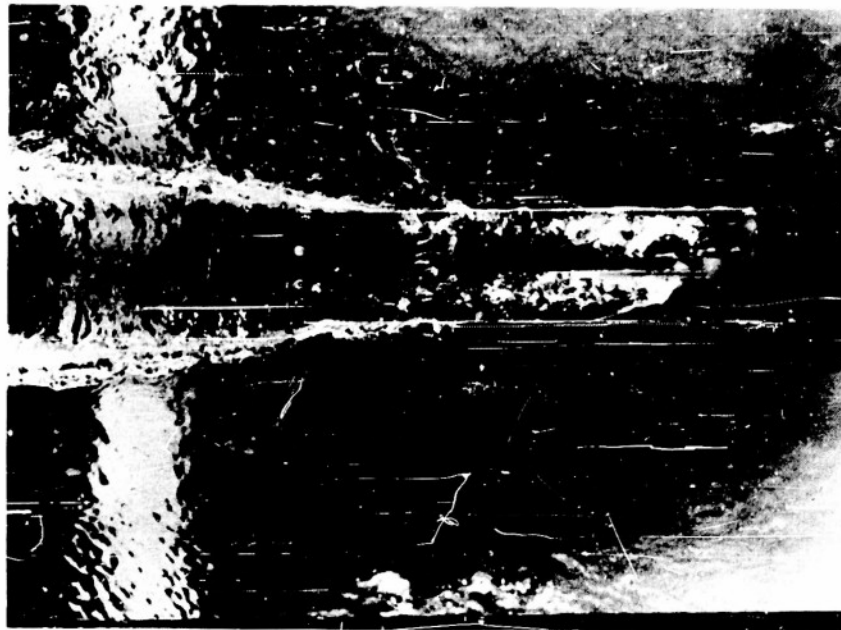
Fig. 3 - Two photographs of the same planing surface taken a few seconds
apart. Note meniscus-like line at plate-water intersection and
also the forward spray clinging to the under side of the plate to
the right of the intersection proper. (Width, 2 in.; wetted length,
2 in.; attack angle, 9°; flow velocity, 12 fps).
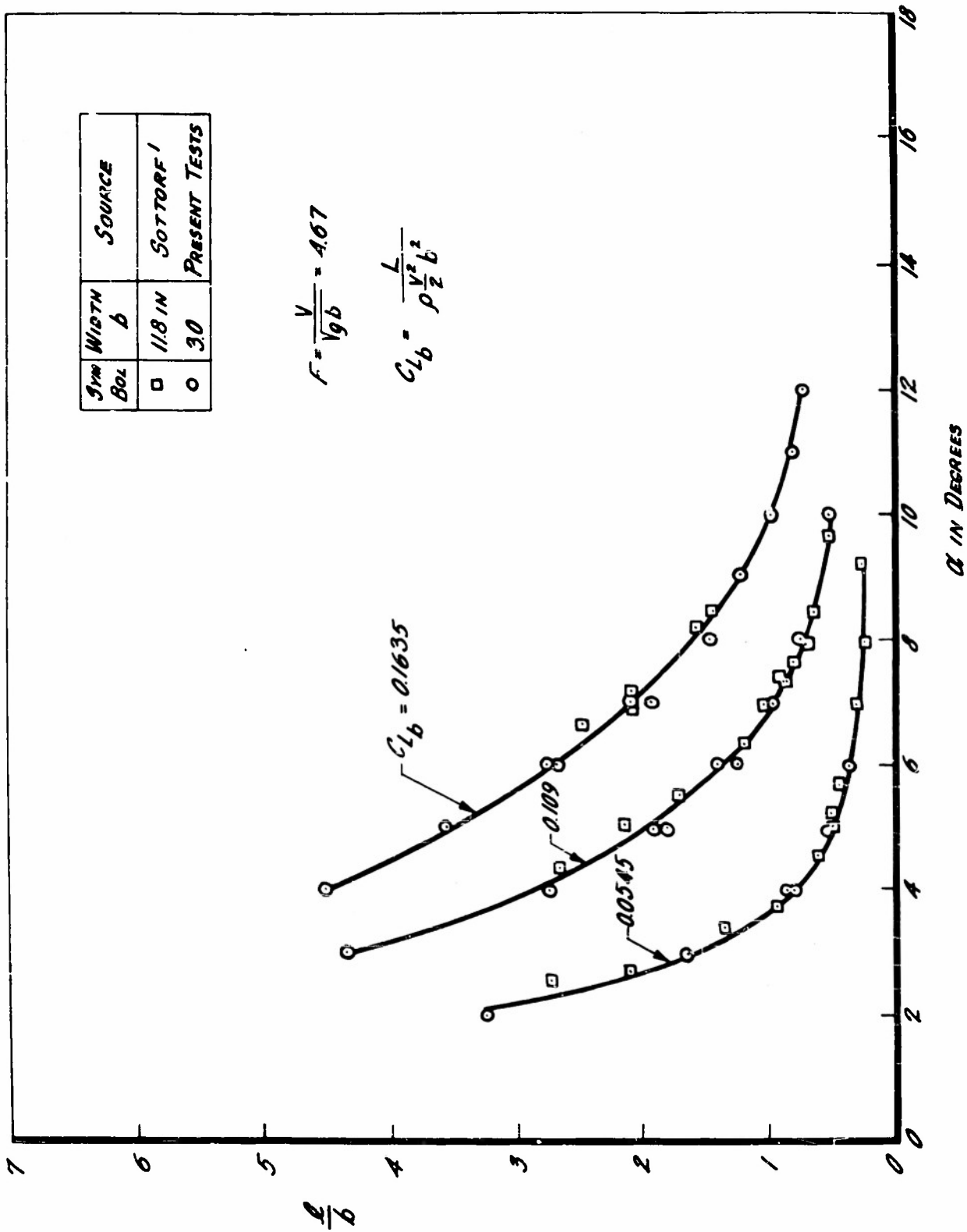
Fig. 4 - Comparison of present tests with those of Sottorf. Measured length-width ratio l/b is given as a function of attack angle α for several lift coefficients C_{L_b} at constant Froude number F = 4.67.
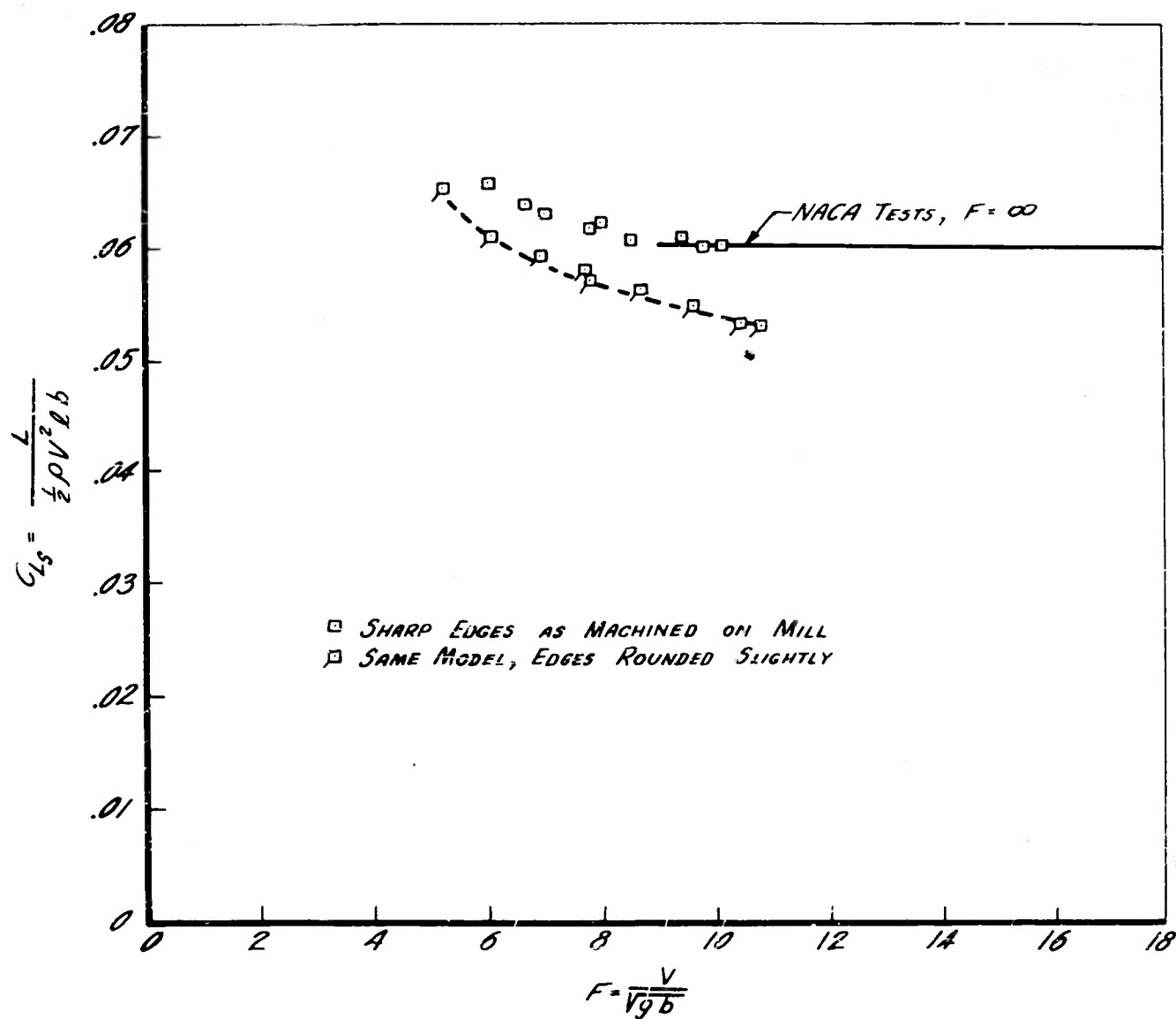
α IN DEGREES

$C_{Lb} = 0.218$

0.109

0.05.45

ℓ/b
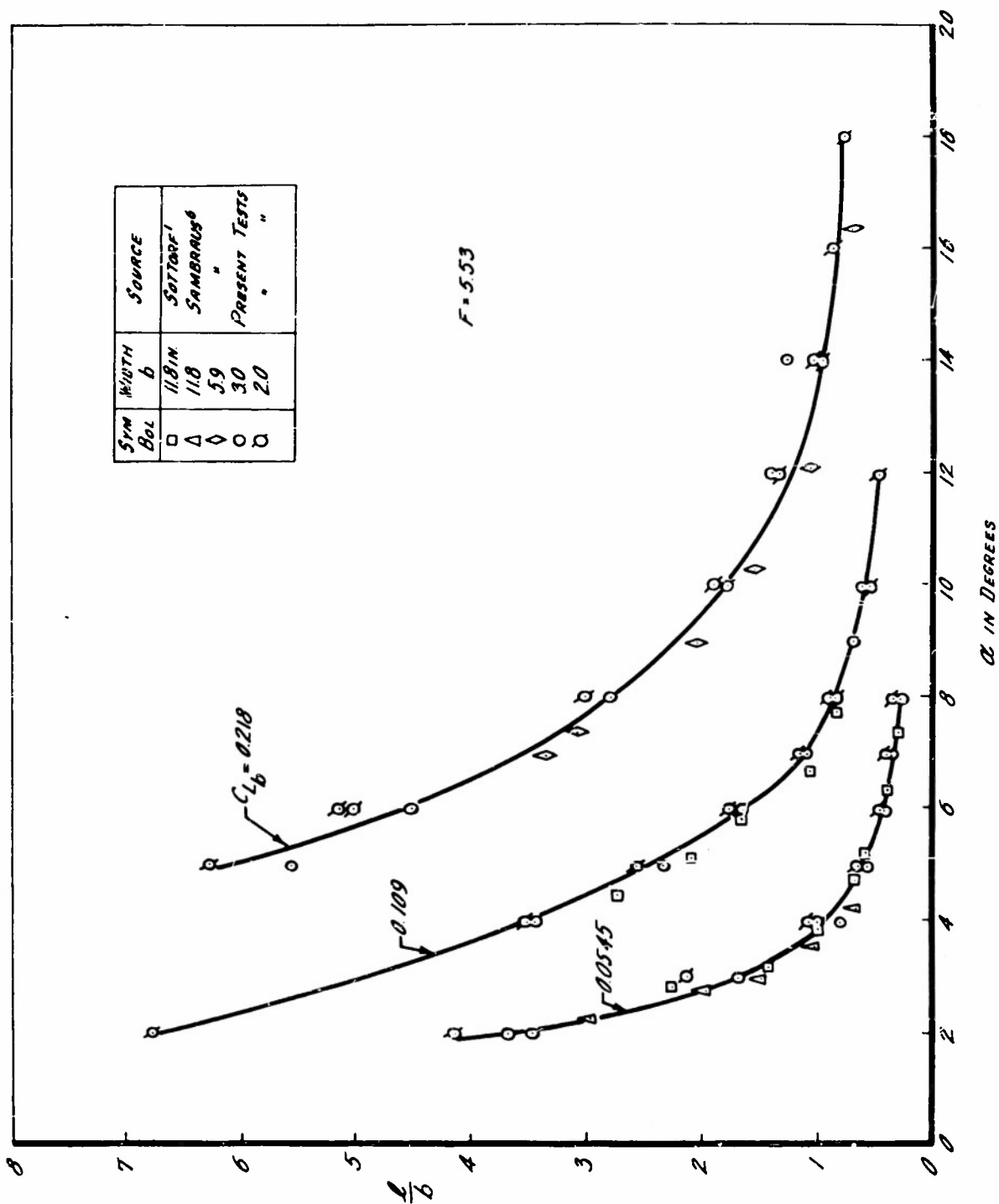
Fig. 5 - Comparison of present tests with those of Sottorf. Measured length-width ratio ℓ/b is given as a function of attack angle α for several lift coefficients C_{L_b} at constant Froude number F = 5.53.

Symbol	Width b	Source
□	11.8 IN	Sottorf[1]
△	11.8	Sambraus[6]
◇	5.9	"
○	3.0	Present Tests
⬭	2.0	"

Fig. 6 - Measurements showing the effect of slight rounding of chines on lift force on a 2-in. width plate; $l/b = 6$, $a = 8°$.
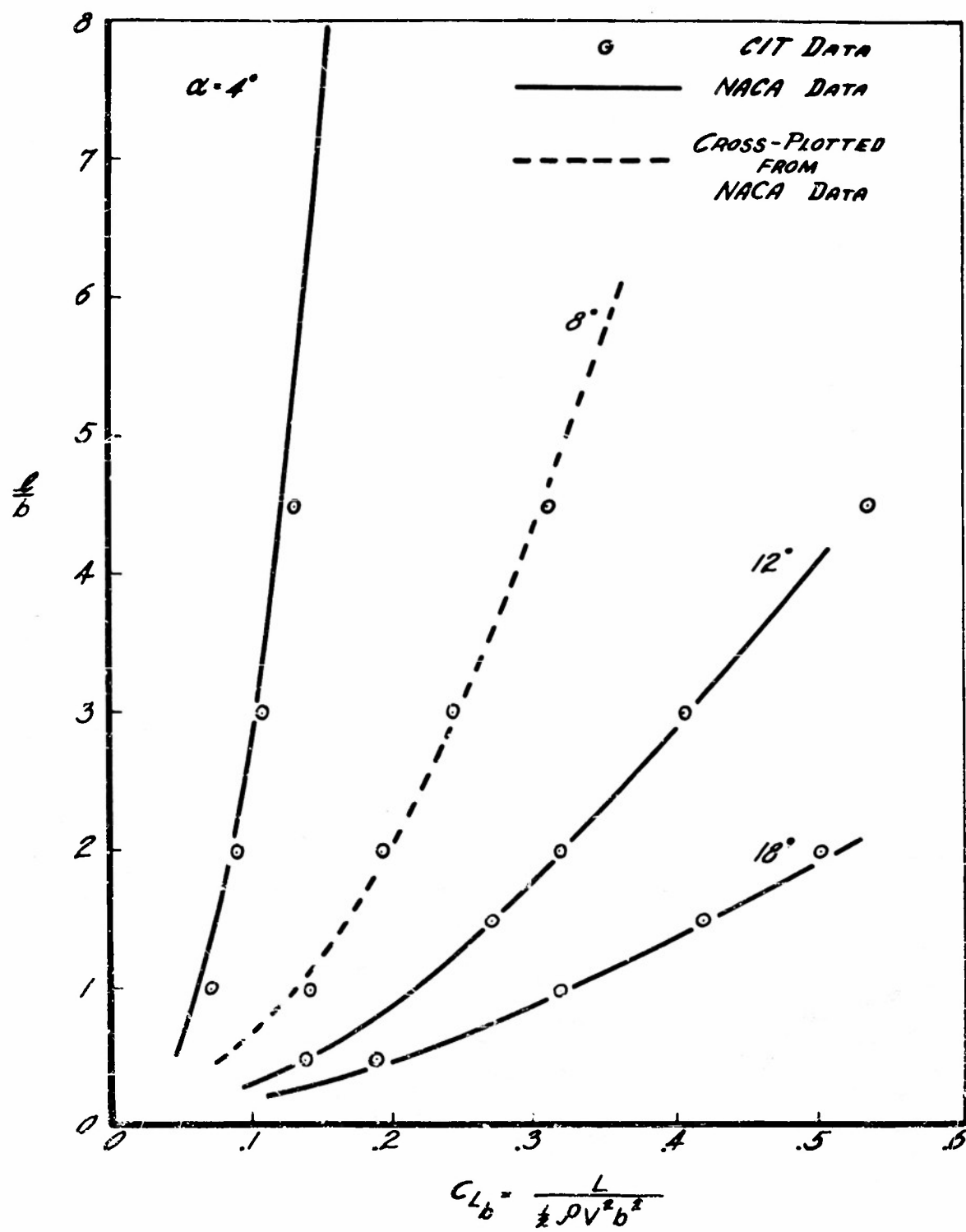
Fig. 7 - Comparison of present measurements with those of NACA.

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